Can the hint of δ_{CP} from T2K also indicate the hierarchy and octant ?

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Introduction

- In neutrino oscillation one flavor evolves into another.
- This is because the flavor eigenstates and mass eigenstates are not same and related by

$$|\nu_\alpha\rangle = \sum_{i=1}^{N} U_{\alpha i}|\nu_i\rangle$$

Where U is the unitary PMNS matrix which diagonalize the neutrino mass matrix

$$m_\nu = U m_\nu^{diag} U^T$$

where $m_\nu^{diag} = diag(m_1, m_2, m_3)$

- In standard three generation framework U can be parametrized by three mixing angles i.e θ_{12}, θ_{13}, θ_{23} and one phase δ_{CP}.

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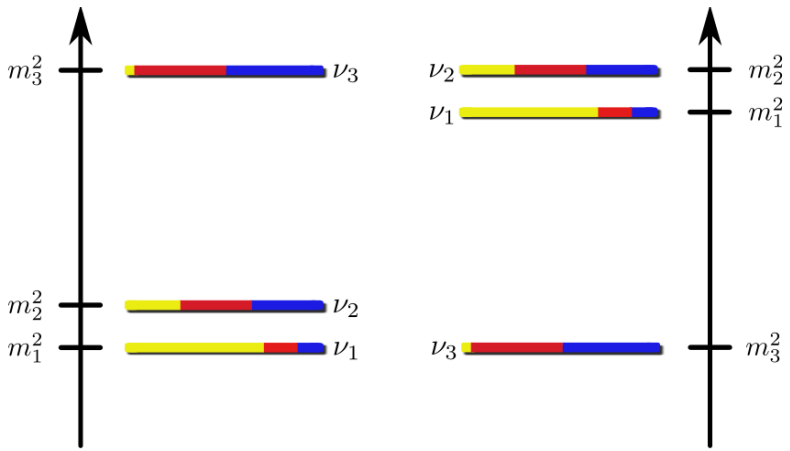
- Neutrino oscillation also involves two independent mass squared difference i.e the solar mass square difference ($m_2^2 - m_1^2 = \Delta_{21}$) and the atmospheric mass squared difference ($m_3^2 - m_1^2 = \Delta_{31}$).



- The undetermined sign of Δ_{31} give rise to two possible mass orderings i.e. Normal Hierarchy(NH i.e $m_3 > m_1$) and Inverted hierarchy(IH i.e $m_3 < m_1$)

Unknowns

- Hierarchy(NH or IH)
- Octant of θ_{23}(LO: $\theta_{23} < 45$ or HO: $\theta_{23} < 45$)
- δ_{CP}(violation and precision)

Current status of δ_{CP}

- Recently, an indication for $\delta_{CP} = -90^o$ has been obtained from T2K data
- This hint comes from T2K running in the "neutrino mode" with 8% of the expected total flux of T2K (7.8×10^{21} protons on target (pot))

The question

In this work we ask the following questions:

- If the T2K hint of -90^o is confirmed by the further T2K 'neutrino' runs, then can it indicate the true hierarchy and true octant ?
- what are the role of anti-neutrinos ?

The T2K experiment

- T2K is a long-base experiment in Japan currently running in neutrino mode
- ν_μ's are shot from J-PARC towards 295 km away Super-Kamiokande detector, which is a Water Cerenkov detector having mass 22.5 kt.
- The flux peaks sharply at the first oscillation maxima around 0.6 GeV

The appearance channel

- For T2K, the probability relevant for the measurement of CP can be expressed in terms of $\alpha = \Delta_{21}/\Delta_{31}$ as

$$P_{\mu e} = 4 s_{13}^2 s_{23}^2 \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

- $\Delta = \Delta_{31} L/4E =$ +ve for NH & -ve for IH
- $A = \hat{A}\Delta_{31} = 0.76 \times 10^{-4} \rho(gm/cc) E(GeV)$
- For anti-neutrinos($\bar{\nu}$) both $\hat{A}$ and δ_{CP} changes sign

Degeneracies in $P_{\mu e}$

- The determination of CP in T2K is affected by degeneracies:

  a)Hierarcy-δ_{CP} degeneracy i.e $P_{\mu e}(\delta_{CP}, NH) = P_{\mu e}(\delta'_{CP}, IH)$
  b)Octant-δ_{CP} degeneracy i.e $P_{\mu e}(LO, \delta_{CP}) = P_{\mu e}(HO, \delta'_{CP})$

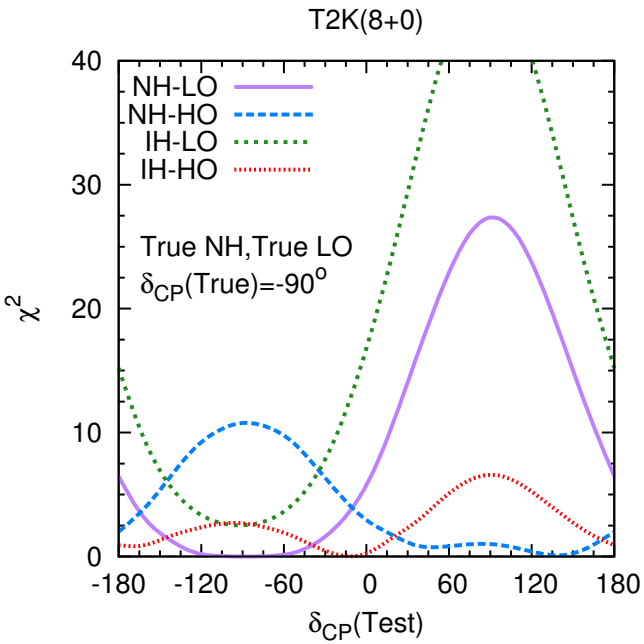
- Due to (a) and (b) there exist 3 fake solutions:

  i)wrong hierarchy-right octant
  ii)right hierarchy-wrong octant
  iii)wrong hierarchy-wrong octant

- As for $\bar{\nu}$, $\hat{A}$ and δ_{CP} both changes sign, addition of $\bar{\nu}$ resolves (b) but not (a) which in turn removes (ii) and (iii) but not (i)

CP Precision

- True value: -90°(motivated by T2K hint)-NH-LO(39°),
- $\chi^2(=(N_{true}-N_{test})^2/N_{true})$ vs δ_{CP}(test) for different test combinations of hierarchy and octant
- 8+0 correspond to running T2K in only ν mode with total 8×10^{21} POT



- 3 best fits: -90, 0, 135
- 0, 135 arises due to the fake IH-HO and NH-HO solutions(wrong octant i.e HO(51°))
- **Conclusion:** If true combination is NH-LO, then clear hint at -90 is not possible.

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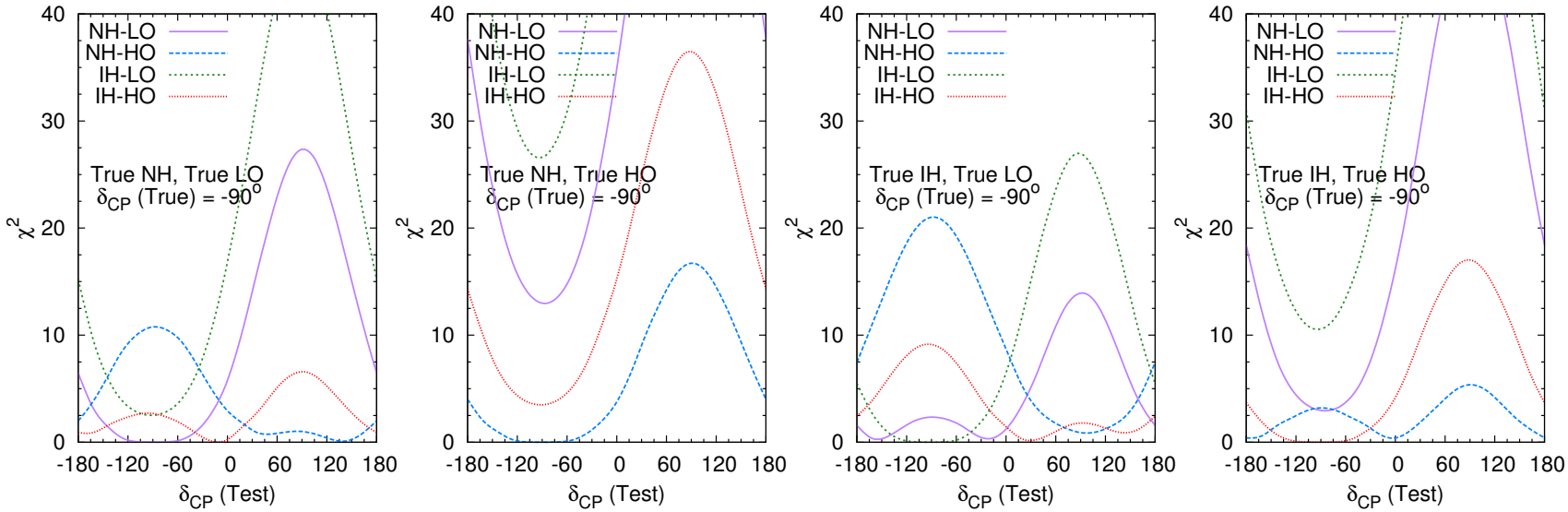
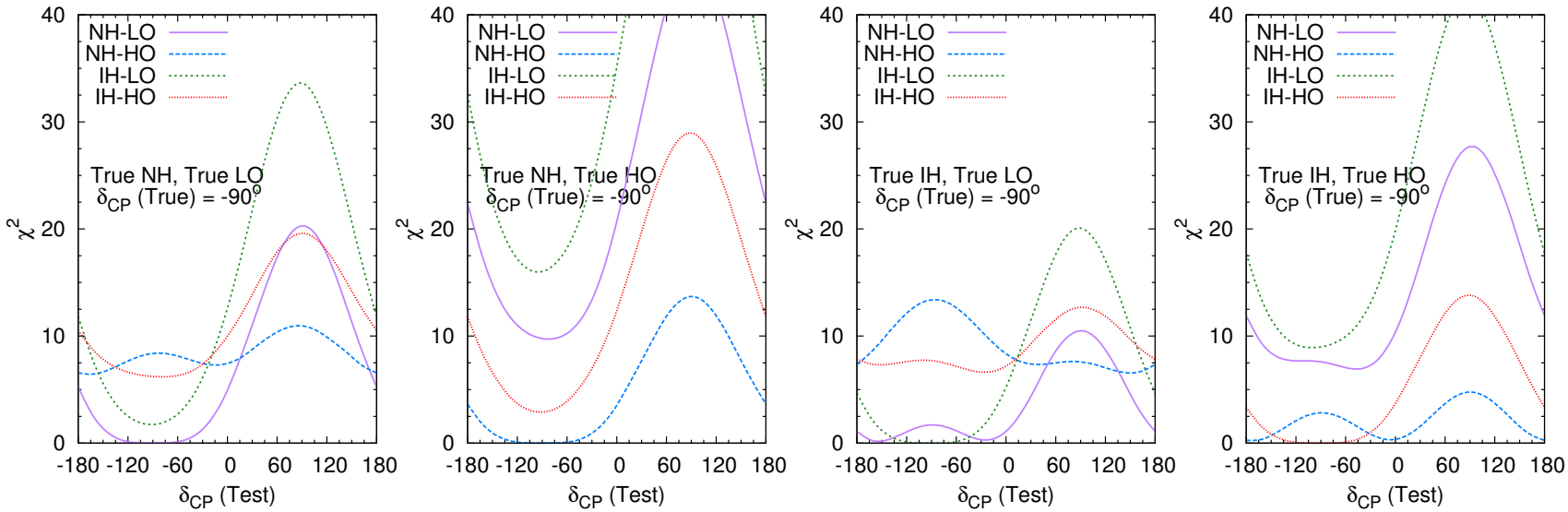
- The same fig plotted for all 4 possible true combinations i.e NH-LO, NH-HO, IH-LO, IH-HO
- T2K config: 8+0



- Only NH-HO gives clear hint at -90
- This is because for ν, -90-NH-HO give to highest event rates
- **Conclusion:** If T2K runs only in ν and gives δ_{CP} = -90, then true hierarchy = NH, true octant = HO

Impact of anti-neutrino run

- T2K config: 4+4



- $\bar{\nu}$ removes the wrong octant fits but not wrong hierarchy fits
- 2nd panel remains unaltered as it does not have any wrong octant best fit
- **Conclusion:** If T2K runs in equal ν-$\bar{\nu}$ and gives δ_{CP} = -90, then
  true hierarchy = NH, true octant =LO, HO

The CP violation discovery χ^2

- To quantify the $\bar{\nu}$ run we study CPV discovery
- The CPV discovery χ^2 is defined as

$$\chi^2 = \min \frac{(N_{ex}(\delta_{CP}^{tr}) - N_{th}(\delta_{CP}^{test} = 0, 180^o))^2}{N_{ex}(\delta_{CP}^{tr})}$$

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$$\begin{aligned} \chi^2 &= 0 \text{ at } \delta_{CP}^{tr} = 0\&180(\text{CP conserving values}) \\ &= \text{max at } \delta_{CP}^{tr} = \pm 90 \end{aligned}$$

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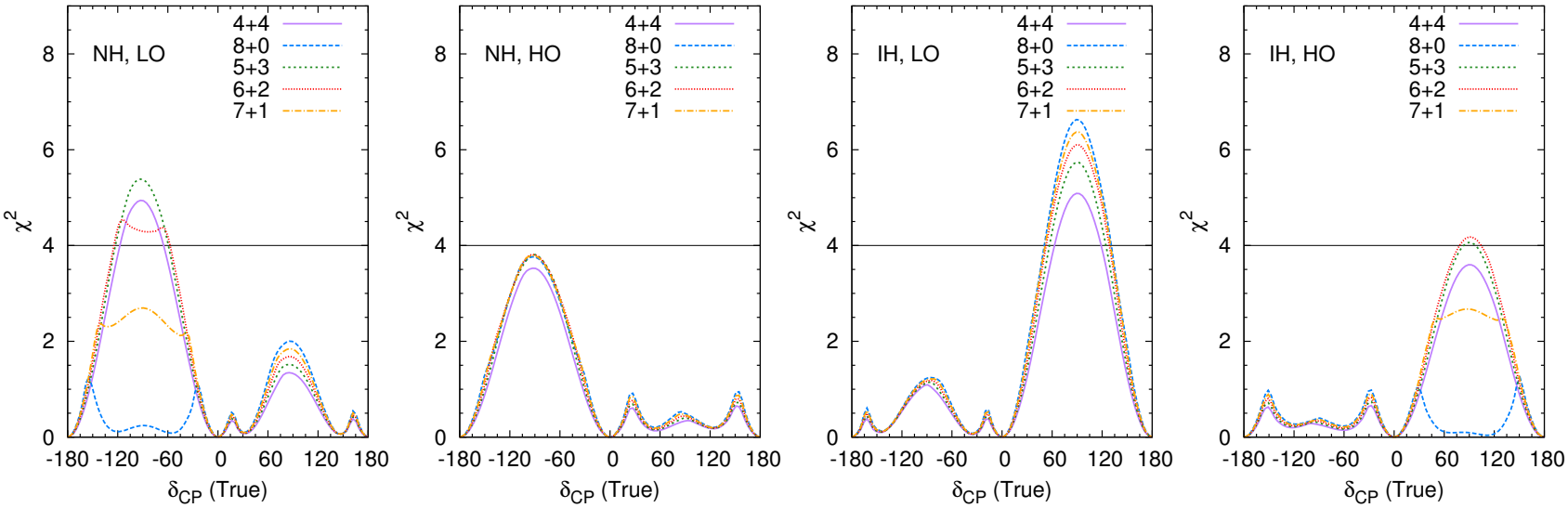
- CPV discovery χ^2 is plotted vs δ_{CP}(true) for all 4 possible true combinations



- For NH-HO and IH-HO, 8+0 is best: addition of $\bar{\nu}$ reduce sensitivity
- For NH-LO, 5+3 and for IH-HO 6+2 is best: further addition of $\bar{\nu}$ reduce sensitivity
- **Conclusion:** $\bar{\nu}$ only removes wrong octant solution if it is present otherwise it reduces sensitivity

The Answer

In conclusion we give the following answers:

- If T2K runs only in ν mode and gives δ_{CP} = -90, then true hierarchy is NH and true octant is HO
- If T2K runs in equal ν-$\bar{\nu}$ mode and gives δ_{CP} = -90, then true hierarchy is NH
- $\bar{\nu}$ only removes wrong octant solution if it is present otherwise it reduces sensitivity

Ghosh, Goswami, Raut : arXiv 1409.5046

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- If T2K runs in equal ν-$\bar{\nu}$ mode and gives δ_{CP} = -90, then true hierarchy is NH
- $\bar{\nu}$ only removes wrong octant soluion if it is present otherwise it reduces sensitivity

Thank You